THERMAL SENSATIONS OF WORKERS IN LIGHT INDUSTRY IN SUMMER. A FIELD STUDY IN SOUTHERN ENGLAND

By D. E. HICKISH, B.Sc.Tech., S.M., A.M.I.E.E., A.M.I.H.V.E.

Department of Applied Physiology, London School of Hygiene and Tropical Medicine

(With 5 Figures in the Text)

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INTRODUCTION

The thermal environment required by an individual for thermal comfort is determined by many factors, including bodily activity, clothing, acclimatization and personal factors such as age and state of health. In describing a comfort zone it is therefore necessary to define the degree of activity, type of clothing, and season to which it is applicable. Houghten & Yagloglou (1923) and Yaglou & Drinker (1928), for example, studied the comfort requirements of normally clothed American adults engaged in sedentary activities in winter and summer respectively, while Partridge & MacLean (1935) confined their investigations to Canadian school-children engaged in quiet activity during summer and then during winter. More recently, Ellis (1952) studied lightly clad naval personnel at meal-times in warships in the tropics, and later (Ellis, 1953) Asian and European men and women engaged in light or sedentary occupations in Singapore. In Great Britain, Vernon & Bedford (1926) made a preliminary investigation of the thermal comfort of men and women engaged in light industrial activities during winter and during summer, and Bedford (1936) developed this approach and studied in greater detail the requirements for winter conditions, determining the comfort zone in terms of several environmental factors. The present investigation is a parallel study to that of Bedford and was designed to obtain information on the thermal comfort zone under summer conditions.

METHOD

The investigation was carried out in five factories in or near London amongst workers engaged in light manual tasks such as the inspection of finished parts, assembly of electrical relays, the filling and packing of cosmetic containers and the operation of office machines. The operatives wore their normal clothing and in many cases a light overall or laboratory coat. Observations were also made at a postal sorting office in London, on postmen wearing G.P.O. uniform and engaged in letter sorting and kindred activities. A total of 2033 persons acted as subjects in the investigation.

The air temperature, humidity, air movement and thermal radiation were measured by means of a whirling hygrometer, silvered kata thermometer (130–125° F. range) and a 6 in. diameter globe thermometer. At each observation position the environmental measurements were made at 2 ft. 6 in. and 4 ft. 6 in. above the floor-level, and the averages of the values for the two levels were

Table 1. *Scale of thermal sensations*

Thermal sensation	Numerical value
Much too warm	+3
Too warm	+2
Comfortably warm	+1
Comfortable	0
Comfortably cool	−1
Too cool	−2
Much too cool	−3

Table 2. *Number of subjects questioned*

Description of occupation	Female	Male	Total
Factory workers	1229	296	1525
Postal workers	12	496	508
Total	1241	792	2033

assumed to represent the conditions to which the trunk was exposed. Concurrently with these measurements the workers in the immediate vicinity were questioned regarding their thermal sensations in a manner similar to that described by Bedford (1936, p. 18) and each reply was interpreted as one of the standard sensations shown in Table 1. For the purpose of statistical analysis, arbitrary numerical values were allotted to these standard sensations. No worker was questioned until at least half an hour after his or her entry into the workshop.

The investigation was made between early May and mid-August. 271 sets of environmental measurements were recorded and 2033 subjects were questioned, as shown in Table 2.

RESULTS

(*a*) *Environmental conditions*

The environmental conditions encountered during the investigation are summarized in Table 3.

(b) *Subjective sensations*

The distribution of the thermal sensations experienced by the workers is shown in Table 4. (For reasons which will be discussed later, the female postal workers have been classed as factory workers.)

Table 3. *Range of environmental conditions encountered*

Thermal index	Range	Mean	S.D.
Air temperature, ° F.	63·1 to 83·0	70·6	3·86
Wet-bulb temperature, ° F.	52·3 to 71·8	60·9	4·17
Globe temperature, ° F.	63·4 to 85·2	72·5	4·20
Equivalent temperature, ° F.	60·1 to 82·4	69·8	4·40
Corrected effective temperature (normal scale), ° F.	60·3 to 76·7	67·8	3·26
Air velocity ft./min.	10·7 to 232	31·5	20·0
Kata cooling power (100° F.)	2·62 to 9·31	5·32	0·93
External air temperature, ° F.	46·9 to 78·7	—	—

Table 4. *Distribution of thermal sensations*

	Frequency of expression		
Thermal sensation	Factory workers	Male postal workers	Total
Much too warm	135	1	136
Too warm	181	31	212
Comfortably warm	421	187	608
Comfortable	714	256	970
Comfortably cool	69	21	90
Too cool	16	—	16
Much too cool	1	—	1
Total	1537	496	2033

(c) *Thermal comfort*

Of the standard sensations listed in Table 1, three (comfortably warm, comfortable, and comfortably cool) denote that the persons concerned were thermally comfortable, and the remaining four denote discomfort. For each interval of temperature, therefore, the percentage of persons who were thermally comfortable may be determined. These percentages are shown in Fig. 1 in relation to dry-bulb temperature. The data used are those for all the factory workers, and the upper figure in each column indicates the number of persons who were thermally comfortable, and the lower figure the total number of persons questioned at the interval of temperature in question.

Previous investigators have defined the comfort zone in terms of the range of temperatures over which the percentage of persons experiencing thermal comfort does not fall below a selected minimum value. Houghten & Yagloglou (1923) and Partridge & MacLean (1935) selected 50 %, Yaglou & Drinker (1928) accepted any percentage above zero, Bedford (1936) used the range in which 70 % of the thermal sensations were 'comfortable' which, in fact, corresponded to at least 86 % experiencing thermal comfort; and more recently Ellis (1952, 1953) has used 80 %.

It seems somewhat optimistic to describe conditions in which 50 % of people feel definitely uncomfortable as coming within the comfort zone. However, the use of Bedford's standard of 70 % of 'comfortable' sensations with the present observations would have failed to give results of practical value for, on account of the wide variability encountered, that standard would have yielded either no comfort zone at all, or with some thermal indices a zone only 2° F. in width. For

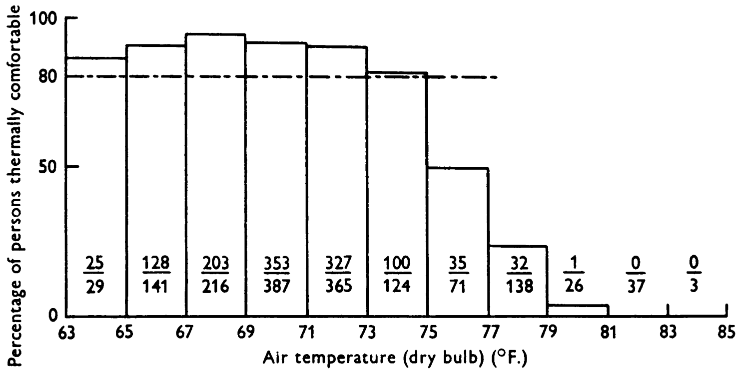

Fig. 1. Percentage of persons thermally comfortable, related to air temperature (dry bulb).

Table 5. *Upper limits of the comfort zone in which not more than 20 % of persons experience discomfort*

Thermal index	Upper limit of comfort zone
Air temperature (dry bulb), ° F.	75
Globe temperature, ° F.	75
Equivalent temperature, ° F.	73
Effective temperature, ° F.	70
Corrected effective temperature, ° F.	71
Dry kata cooling power (minimum value)	4·5

this reason Ellis's standard, which required that at least 80 % of persons should be thermally comfortable, has been used with the present data. The upper limits of the comfort zone in terms of various thermal indices are given in Table 5. The lower limits of the zone were not obtainable from the data, as the thermal conditions encountered were such as to produce sensations of warmth rather than of coldness.

(*d*) *The regression of thermal sensation values upon various thermal indices*

The method of analysis employed in the previous section gives only a limited amount of information. It does not, for example, indicate the temperature considered to be the most desirable by the majority of subjects. The use of regression analysis provides a convenient method for more detailed investigation of the relationship between thermal sensations and thermal indices of the environment. The numerical values assigned to the standard sensations shown in Table 1 are quite arbitrary, but evidence of a linear relationship between the mean values of thermal sensations and thermal indices was shown by Bedford in his study of winter conditions in factories. The data for thermal sensations and dry-bulb temperature for all factory workers are given in Table 6, and are represented

Table 6. *Distribution of thermal sensation values experienced by factory workers in relation to dry-bulb temperature*

Dry-bulb temperature (° F.)	Frequency of expression of thermal sensations −3	−2	−1	0	+1	+2	+3	Total	Mean thermal sensation
63–	1	3	8	16	1	—	—	29	−0·55
65–	—	10	26	87	15	3	—	141	−0·18
67–	—	3	11	155	37	10	—	216	+0·19
69–	—	—	13	221	119	33	1	387	+0·45
71–	—	—	11	169	147	34	4	365	+0·59
73–	—	—	—	51	49	20	4	124	+0·82
75–	—	—	—	11	24	22	14	71	+1·55
77–	—	—	—	4	28	42	64	138	+2·20
79–	—	—	—	—	1	7	18	26	+2·65
81–	—	—	—	—	—	9	28	37	+2·76
83–	—	—	—	—	—	1	2	3	+2·67
Total	1	16	69	714	421	181	135	1537	—

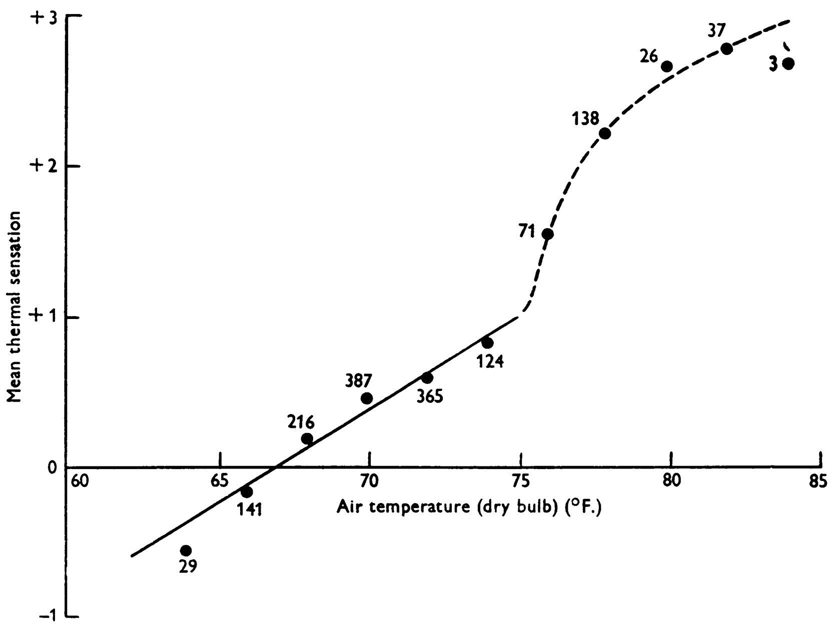

Fig. 2. Mean thermal sensations for all factory workers studied, related to air temperature (dry bulb).

graphically in Fig. 2. The numbers shown alongside the points on the graph indicate the number of observations from which the mean thermal sensation has been derived.

It is apparent from Fig. 2 that while there is good evidence of a linear relationship at the lower temperatures, there is at higher temperatures an abrupt increase of slope followed by a flattening of the curve. This latter effect is to be expected, as with the sensation scale used the mean thermal sensation at any temperature cannot exceed a value of + 3, indicating that all the subjects feel much too warm. The reason for the abrupt change of slope at a temperature of about 75° F. is less apparent. This effect was not found by Bedford during the winter studies, but the range of conditions encountered then did not extend beyond that over which the linear relationship was noted in the present study. Examination of the data of Ellis (1952) (Table 7) does, however, indicate a similar effect at about 86° F. (Fig. 3). Ellis's observations were made over a range of dry-bulb temperatures of 77–94·9° F., associated with a wet-bulb range of 70–84·9° F. and effective temperature range 72–85·9° F.

Table 7. *Mean thermal sensation, percentage of subjects sweating and percentage of subjects stripped to the waist related to air temperature* (*Ellis*, 1952)

Dry-bulb temperature	Mean thermal sensation*	Percentage of subjects sweating	Percentage stripped to the waist
77–	−0·40	0	26·5
81–	+0·22	5·6	33·3
82–	+0·25	0	75·5
83–	+0·43	12·5	54·5
84–	+0·49	12·9	42·7
85–	+0·65	12·1	59·1
86–	+1·04	33·7	92·3
87–	+1·37	42·6	89·9
88–	+1·49	37·2	100·0
89–	+1·67	50·5	100·0
90–	+1·80	72·0	100·0
92–	+1·97	69·1	100·0
93–	+2·00	65·1	100·0
94–	+2·64	92·3	100·0

* This column has been computed from the data of Ellis.

Ellis also gives the percentage of subjects who reported perspiration on face or chest. It will be noted that the sudden rise in mean thermal sensation is accompanied by a corresponding rise in the percentage of subjects who were sweating. There is thus a suggestion that the onset of sweating may be accompanied by a change in thermal sensation from comfort to discomfort. Kuno (1934) and Winslow, Herrington & Gagge (1937) respectively, have shown that in nude persons, sweating commences at an air temperature of about 86° F. and evaporative heat loss increases rapidly at higher temperatures. The majority of Ellis's subjects were stripped to the waist at the time of observation, and may reasonably be compared to nude subjects. Winslow, Gagge & Herrington (1938) report that for clothed resting subjects, the rapid increase in heat loss by evaporation occurs at about 76° F.—i.e. at roughly the temperature at which the change in thermal sensation is noted amongst factory workers in the present study.

Winslow, Herrington & Gagge (1937) have also shown that when the mean skin temperature of a clothed subject reaches 95° F. (35° C.) a sharp increase in sweat secretion occurs. It may readily be calculated from the formulae used in determining clothing insulation values (Newburgh & Harris, 1945) that the mean skin temperature of a resting subject will approximate to 95° F. in an environment at 75° F. with low air movement if the insulation of the clothing worn is of the order of 0·75 clo. unit. [1 clo. unit is the amount of clothing required by a resting subject in an atmosphere of 70° F., relative humidity below 50 % and air movement 20 ft./min., in order that the subject may remain thermally comfortable (Gagge, Burton & Bazett, 1941).] Determinations of the insulation values of the

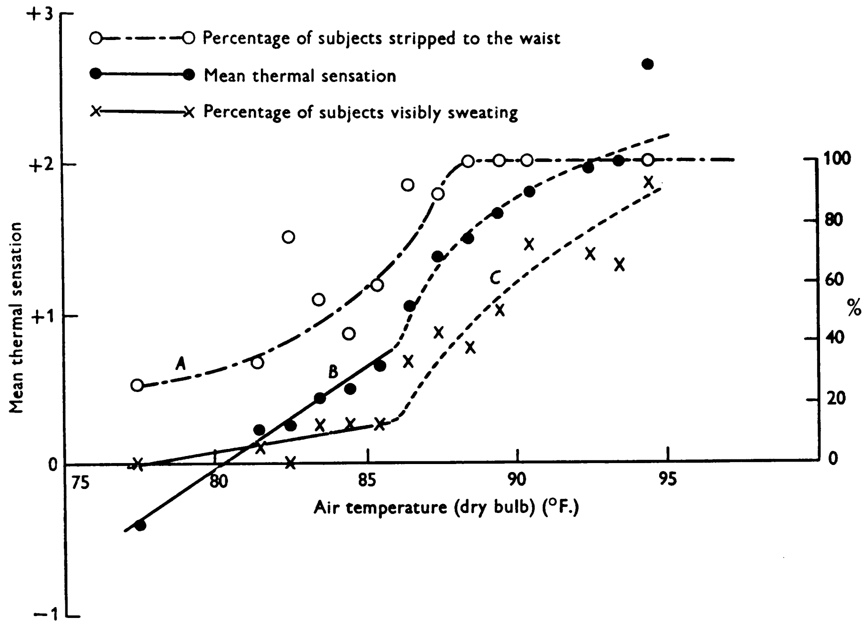

Fig. 3. Mean thermal sensations, percentage of subjects stripped to the waist, and percentage of subjects visibly sweating, related to air temperature (dry bulb) (Ellis, 1952). (Dry bulb range 77–94·9° F. associated with wet-bulb range 70–84·9° F. Effective temperature range 72–85·9° F.).

clothes worn by the factory workers were not made experimentally, but as light summer clothing was worn, the value would be in the region of 1 clo. unit. Sweating might, therefore, be expected to occur beneath the clothing at temperatures of 75° F. and above.

The results of the present study show that there is a critical temperature above which thermal discomfort is rapidly experienced by the majority of subjects, and, in the light of what has just been said, it is suggested that this effect may be due to the onset of sweating beneath the clothing. This critical temperature, therefore, may be considered to be the upper limit of the comfort zone for workers of the type studied, and the values of this limit in terms of the various thermal indices are shown in Table 8.

Regression analysis has been applied to the linear portions of Fig. 2 and the corresponding graphs for other thermal indices, and the regression equations are then expressed as:

$$y = bx + c,$$

where y = mean thermal sensation, x = value of the thermal index, and b and c are constants. The value of the thermal index for optimum comfort is that corresponding to a mean thermal sensation of 0 (i.e. 'comfortable') and may be calculated from the appropriate regression equation. Values of the regression constants and optimum values of the thermal indices are given in Table 9.

Table 8. *Upper limits of comfort zone based upon departure from linearity of the regression of mean thermal sensation upon various thermal indices.*

Thermal index	Upper limit of comfort zone
Air temperature (dry bulb), ° F.	75
Globe temperature, ° F.	75
Equivalent temperature, ° F.	73
Effective temperature, ° F.	70
Corrected effective temperature, ° F	71
Dry kata cooling power (100° F.) (minimum value)	4·0

Table 9. *Constants in the regression equations of thermal sensation upon thermal index and optimum conditions for comfort*

Thermal index	Constant b	Constant c	Optimum condition
Air temperature (dry bulb), ° F.	0·122	−8·15	66·8
Globe temperature, ° F.	0·108	−7·40	68·5
Equivalent temperature, ° F.	0·105	−6·92	65·9
Corrected effective temperature, ° F.	0·123	−7·92	64·4
Dry kata cooling power (100° F.)	−0·491	+3·1	6·3

Table 10. *Correlation and prediction constants*

Thermal sensation correlated with:	Correlation coefficient r	σy	$\sigma y \sqrt{(1-r^2)}$
Air temperature (dry bulb)	0·377	0·722	0·668
Globe temperature	0·371	0·636	0·591
Equivalent temperature	0·368	0·653	0·607
Corrected effective temperature	0·340	0·700	0·659
Dry kata cooling power	−0·381	0·874	0·808

The correlation coefficients (r) for the linear portions of the graphs are given in Table 10. Also given are the values of the standard deviations of the thermal sensations (σy) and the values of the standard deviation of the differences between actual and predicted values of $y[\sigma y \sqrt{(1-r^2)}]$. The values of σy vary, due to the fact that the observations comprising the linear portions were not identical for each thermal index.

It is apparent that while the mean thermal sensation for a group of persons may be predicted from thermal measurements with reasonable accuracy, such prediction of individual thermal sensations is very inaccurate.

(*e*) *Personal factors and their influence upon thermal sensations*

(i) *Clothing*

The male postal workers differed from the factory workers in that they were required to wear regulation uniform made from either summer-weight or winter-weight material, whereas the factory workers were free to vary their clothing as they desired. The degree of activity was very similar in the two groups, and any difference in thermal requirements is thus likely to be due to the difference in clothing. The thermal needs for men of both groups are compared in Fig. 4 and Table 11, in terms of air temperature, the optimum temperature for the postal workers being estimated by extrapolation. Owing to the large thermal capacity of the postal building compared with that of the other factories, the temperatures encountered there were lower than elsewhere.

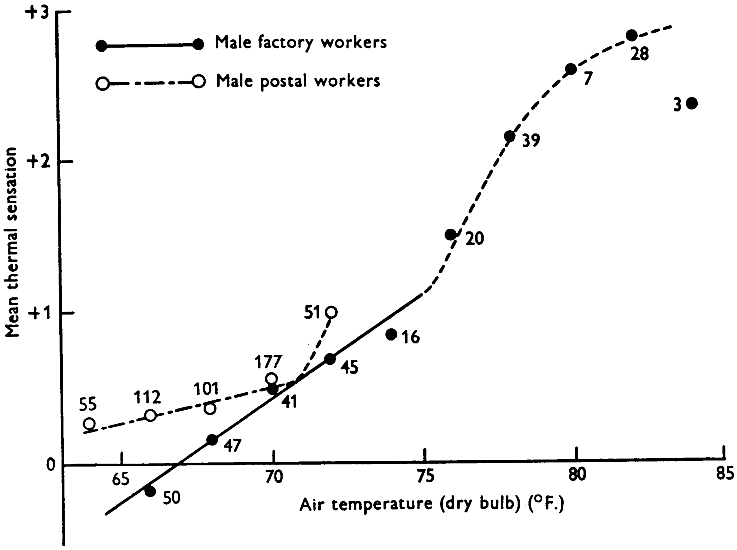

Fig. 4. Mean thermal sensations for male factory workers and postal workers, related to air temperature (dry bulb).

Table 11. *Regression constants and optimum air temperatures (dry dulb) illustrating effect of clothing*

Subjects	Regression coefficient *b*	Constant *c*	Optimum air temperature (dry bulb) (° F.)
Postal workers (male)	0·051	−3·03	59·8
Factory workers (male)	0·136	−9·12	67·0

The upper limit of the comfort zone for the postal workers cannot be stated precisely owing to the small number of observations at the higher temperatures, but it appears to occur in the region of 71° F., i.e. about 4° F. lower than for the factory workers.

(ii) *Sex differences*

The results of the comparison of thermal requirements of (*a*) male factory workers, and (*b*) female factory workers and postal workers are shown in Fig. 5 and Table 12. The female postal workers have been included with the factory workers since those questioned were temporary staff who were not required to wear uniform.

The regression coefficients are not significantly different ($t = 0{\cdot}760$, while t for $P = 5\%$ is 1·960), and the optimum temperatures differ by only 0·3° F., a difference of no practical importance. It is evident, therefore, that provided there is personal freedom in the choice of clothing, men and women factory workers in light occupations do not require different thermal conditions.

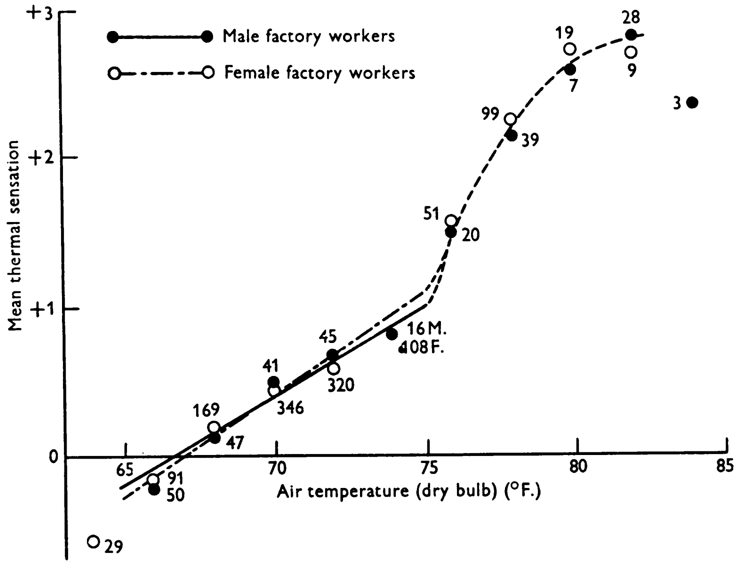

Fig. 5. Mean thermal sensations for male and female factory workers, related to air temperature (dry bulb).

Table 12. *Regression constants and optimum air temperatures (dry bulb) for male factory workers*

Group	Regression coefficient b	Constant c	Optimum air temperature (dry bulb) (° F.)
Female factory workers	0·119	−7·94	66·7
Male factory workers	0·136	−9·12	67·0

DISCUSSION

Reference has been made to the investigation by Bedford of the winter comfort zone for factory workers engaged in a degree of activity similar to that of the workers in the present study. A comparison of the results of the two investigations is given in Table 13. The upper limits of the winter zones have been derived from the original data, on the basis of the temperatures at which not more than 20 % of the subjects experienced discomfort. I am indebted to Dr Bedford for permission to quote the values of the optimum condition and upper limit in terms of corrected effective temperature which have been derived since the original publication (Bedford, 1954*a*, *b*).

The optimum conditions and upper limits of the summer comfort zone appear to be generally 2–4° F. higher than those of the winter comfort zone, according to the thermal index used. The summer and winter comfort zones for normally clothed persons engaged in sedentary activity in the U.S.A. have been determined by Yaglou & Drinker (1928) and Houghten & Yagloglou (1923) as 64–79 and 60–74° F. respectively, effective temperature being used as the thermal index. These zones, however, are those in which one or more persons did not experience discomfort. If the criterion is applied that not more than 20 % of persons should experience discomfort, the zones then become 69–74 and 65–69° F. The upper comfort limit thus appears to have a similar seasonal variation of 4–5° F. effective temperature in both countries.

Table 13. *Comparison of the thermal requirements of factory workers in winter and summer*

	Winter		Summer	
Thermal index	Optimum condition	Upper limit	Optimum condition	Upper limit
Air temperature, ° F.	64·7	72	66·8	75
Globe temperature, ° F.	65·1	74	68·5	75
Effective temperature, ° F.	60·8	66	62·9	70
Corrected effective temperature, ° F.	61·7	68	64·4	71
Equivalent temperature, ° F.	62·3	70	65·9	73
Dry kata cooling power (100° F.)	6·06	4·5	6·3	4·5

The importance of the consideration of the clothing worn in determining thermal comfort zones is illustrated in the present study by the difference in response to similar thermal environments of the postal workers wearing uniform clothing, and the factory workers who were free to adjust the amount of clothing worn. Yaglou & Messer (1941) showed that differences between the comfort standards of men and women are largely due to differences of dress, and can be reconciled by adjustment of clothing. The virtual identity of the requirements of men and women in the present investigation may perhaps indicate that with freedom of choice, approximately equal amounts of clothing were worn by both sexes.

SUMMARY

Workers in factories and a postal sorting office were questioned concerning their subjective thermal sensations, and the replies assessed according to a scale of standard sensations. Measurements of the thermal environment were made concurrently. The investigation was confined to workers engaged in light or sedentary activity during summer months in southern England.

The upper limit of the comfort zone is determined in terms of the temperatures at which more than 20 % of people questioned experienced thermal discomfort.

Discontinuities in the linear relationships between thermal sensation, described on a numerical scale, and the thermal indices of the environment are shown to occur under conditions which suggest the onset of sweating beneath the clothing. The comfort zone is also determined in terms of these critical temperatures.

The regression constants relating thermal sensation to thermal conditions are determined, and the optimum conditions for comfort are deduced. The accuracy of prediction of thermal sensation from thermal measurements is examined.

The importance of clothing in requirements for thermal comfort is illustrated in two ways. Postal workers wearing regulation uniform were found to require conditions cooler than those required by factory workers wearing clothing of their own choosing. Male and female factory workers were found to require thermal conditions not significantly different, this being attributed to their selection of clothing appropriate to their personal thermal requirements.

I am indebted to Prof. G. P. Crowden for granting facilities for this research and for encouragement throughout. Dr T. C. Angus and Dr T. Bedford gave valuable advice, and Mr P. J. Williams rendered technical assistance. The co-operation of the managements and workers at the factories was greatly appreciated.

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